The Association

of

Engineering and Shipbuilding Draughtsmen.

THE CASE-HARDENING OF STEEL

By A. CRAIG MACDONALD, B.Sc., A.M.I.A.E.

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INTRODUCTION.

In the minds of many of those engineers and other technicians who periodically come in contact with case-hardening and similar heat-treatment processes, there exists a great deal of doubt concerning the principles involved, the mechanics of the operations, and the necessity for the "delay" when steel parts "go through the furnace." Far too much mystery surrounds the perfectly straightforward methods which are employed in these days to render stressed parts and wearing parts capable of doing their bit throughout the life of the unit of which they are components, and the author attempts in the following pages to clear up some of the mystery by outlining the fundamentals which control the more important surface-hardening processes.

As this pamphlet is primarily intended for engineers, there is no need to emphasise the importance of the surface-hardening of steel in relation to modern prime movers and other units comprehensively described as "machinery." Our ability to make moving parts very resistant to wear under heavy loads has enormous advantages that are not always appreciated and remarkable results are achieved in everyday practice. When gloomy discussions are in progress anent the necessity to eliminate wear in a particular piece of mechanism, and a few thousandths of an inch of wear after millions of revolutions are greeted with groans of despair, the author is tempted to point out that the figures, however inconvenient their effects may be, are in actual fact an astonishing tribute to the engineer and the metallurgist—and their ingenuity is not yet exhausted.

Before proceeding any further, the author would like to have it clearly understood that in order to make this pamphlet complete in itself, it would be necessary for him to begin by explaining all the principles involved in the heat-treatment of steel and the factors which must be taken into account in developing the properties of carbon and alloy steels by heating and cooling processes. Unfortunately attempts to do this in a few words are never successful, and a great deal of available space would be occupied by these preliminary explanations. The author, therefore, proposes to continue on the assumption that the reader is already familiar with the information given in the author's previous pamphlet on "The Heat-Treatment of Steel," published by the A.E.S.D. during session 1934-35. In that publication he gave the essential details of the

compositions of steels which respond to heat-treatment ; he described as simply as possible the effect of the carbon content and the effect of other elements on the methods adopted, and the results obtained ; the meaning of terms like normalising, annealing, hardening (as distinct from case or surface hardening), tempering, eutectoid, critical temperatures, ferrite, cementite, pearlite ; the importance of grain size and the mass of the part—all with diagrams and tables to amplify the text. In that pamphlet, as in this, the author concentrates on those points which are of interest and practical value to the engineer, and matters of purely metallurgical importance are left severely alone.

The fact that soft iron or steel could be surface-hardened by various methods was discovered in the very early days of working these metals, and skilled craftsmen had their own particular and jealously-guarded system of imparting this skin-hardness to their implements. While one man spent laborious days trying unsuccessfully to harden files by heating them and cooling them in countless different ways, another more knowledgable individual would hug to himself the valuable secret that if these tools were heated for some time while surrounded by a repulsive mixture mainly composed of rats' tails, they would subsequently harden in what was then regarded as a truly marvellous fashion. But he in turn would never be convinced that anything but rats' tails would do the job, whereas in actual fact almost any carbonaceous matter would be, in some degree, successful.

Iron and steel have the useful property of absorbing carbon when heated to temperatures over 760°C. in contact with that substance. Just as carbon steel is "decarburised" at high temperatures in an oxidising atmosphere, it will in turn be "carburised" under the special conditions aforementioned. Both processes can be continued to a remarkable extent. While steel is being decarburised in an oxidising atmosphere and the outer skin becomes carbon-free iron, the carbon tends to diffuse outwards to the carbonless area which absorbs it and in due course loses it again to the oxidising gases with which it is in contact. And so the process goes on until, under appropriate conditions maintained for a long time, the piece of steel loses its carbon throughout its mass. Similarly when steel is absorbing carbon from a suitable medium, the lower carbon areas under the skin absorb carbon from the carburised surface which makes up the loss by further absorption from without, and the process can be continued until the steel has attained a high carbon content for a considerable depth.

Now, as the author has explained elsewhere, a low carbon steel cannot be hardened to any appreciable extent (by heating and quenching) whereas a high carbon steel can attain considerable hardness by a simple heat-treatment process. In addition, it has to be borne in mind that low carbon steels retain considerable ductility and resistance to shock when attempts are made to harden

them by heating and quenching, whereas high carbon steels become very brittle when hardened in this fashion—although the hardness so induced may be very desirable indeed.

It is easy to understand then that when a piece of low carbon steel is "carburised" so that the surface has a high carbon content, we find ourselves in possession of a very useful bit of material, which, when heated to the proper temperature and quenched in (say) water, will develop great surface hardness and yet its core will retain the toughness which is so necessary to many wearing parts. That is one of the main virtues of the carburising or case-hardening operation.

The reader may, of course, think immediately of quite a number of parts in the machines with which he is familiar which are case-hardened and which at the same time do not require to possess any particular degree of toughness or resistance to shock. If they were so brittle that they would break if allowed to fall on the floor, their duty is such that they would perform it adequately as long as they were just hard. Well, there are quite a number of reasons why such parts are made of low carbon steel case-hardened instead of high carbon tool steel hardened by heating and quenching.

In the first place, we must recognise that there are wearing parts manufactured to-day by the case-hardening process when there is no economic or metallurgical reason why they should not be machined from high carbon steel and hardened in the ordinary way. But they are small parts of simple shape and light duty, otherwise they would be made from low carbon steel case-hardened, for the following reasons :—

(*a*) Unless a wearing part is very small it is actually cheaper to manufacture it from cheap low carbon steel and subsequently harden its surface by the case-hardening process, rather than to manufacture it from relatively dear high carbon steel even when there is no necessity for a tough core.

(*b*) Only parts of simple shape can be made of high carbon steel and subsequently hardened thoroughly without the risk of cracks developing. The internal stresses set up in hardening this type of steel are considerable (particularly in the case of the very high carbon contents necessary to get that coveted "glass-hard" surface) and at changes of section, fillets, keyways, spline roots, etc., cracks are liable to develop when the whole mass is composed of the high carbon material in question. When the main body of the material is low carbon steel, which does not develop such high internal stresses in the quenching operation, the latter can be carried out with much less fear of scrapping the part. In many cases, too, the dangerous places can be kept free of carbon even on the surface by selective carburising—but more of that anon.

(*c*) One other reason for the use of the case-hardening method when core toughness does not at first glance appear to be required, is well worthy of mention. The soft core can have a valuable "cushioning" effect distinct altogether from resistance to fracture by ordinary shock or deformation. The glass-hard surface of the case-hardened part is less liable to crack and flake and be crushed in service when its comparatively soft core allows a certain amount of temporary accommodation to the stresses imposed. It is easy, of course, to imagine conditions under which the soft core would allow the hard skin to be crushed like an eggshell, but in a satisfactorily designed unit wherein the surfaces of a wearing part receive adequate support from its core, the cushioning effect the author has attempted to describe is undoubtedly of importance.

These are all reasons why the case-hardening method is frequently adopted when there is apparently no necessity to pass by the high carbon steels, but in giving these reasons due attention we do not want to overlook the fact that the greatest value of the case-hardening process lies in its ability to produce very hard wear-resistant surfaces on parts which require a tough core to resist the shocks and stresses of severe service.

It would be advisable now to describe a typical case-hardening process in general terms before giving the details of the steels used, the results obtained, and the accessories necessary for satisfactory working.

Typical Process.

The parts to be hardened should arrive in the heat-treatment department reasonably clean and dry. There they are packed in metal boxes in such a way that each is completely surrounded by an adequate quantity of the carburising compound. When the boxes are full the lids are put on and sealed with fireclay paste. The boxes are then transferred to a muffle furnace and raised to the carburising temperature (say 920°C.) at which temperature they are held for some hours, the time depending on the case depth required. Immediately it has been decided that the carburising period is complete, the boxes are withdrawn from the furnace and taken out into the open air where they are allowed to cool freely. When cold, the boxes are opened, the parts are extracted, and the used compound is stored in a suitable receptacle.

Now the parts at this stage are still very soft. The surface will be found to give a higher Brinell hardness than before, but only because the said surface is now that of a higher carbon steel than the original material. But even a high carbon steel is soft in the annealed condition—and that is the condition of parts cooled

comparatively slowly from the carburising temperature. A heat-treatment process then follows the carburising operation. This may involve simply a single heating and quenching which renders the case glass-hard, or on the other hand, two such heatings and quenchings may be considered necessary in order that the core as well as the case shall be satisfactory for service. We shall postpone discussion of these re-heat-treatment processes until we are dealing with the individual types of steel used for case-hardening purposes.

Now that the typical process has been described as simply as possible in order that the reader may get a mental picture of the whole operation, it should be mentioned that a host of essential figures and detail have been left out. These we shall supply now to the best of our ability.

This typical process we have described is known as a "pack-hardening" process. That almost self-explanatory title distinguishes it from hardening in liquid baths, gas retorts, etc. Pack-hardening is deservedly popular and is generally recognised as still the most all-round satisfactory method of carrying out the case-hardening process (for reasons which will possibly emerge as we proceed).

In different factories employing the pack-hardening process, some variations may be observed in the equipment used and in the mechanics of the operations involved, but the fundamental principles remain unaltered and the author's purpose will be well served if he succeeds in describing adequately the particular method of pack-hardening which he himself regards as the most satisfactory for producing economically the highest class of work. Here are the details.

Compound.

The basis of these compounds is wood charcoal. Hard wood charcoals are the best (they resist crumbling) and of these beech is the most commonly used. Charcoal alone, however, carburises very slowly (although it produces a very satisfactory type of case) and some form of energiser is required for economic working. This arises from the accepted fact that during the carburising operation the actual work is done by the gaseous products of the slow combustion of the compound. Carbon monoxide is probably the most active agent. The energisers mentioned act more or less as catalysts. They themselves are frequently unchanged by the process, but by their very presence they increase greatly the activity of the gases in carburising the steel.

These so-called energisers are essential for satisfactory working, but they must be used with discretion because they can have the effect of super-saturating the case with carbon and the free cementite so formed will give endless trouble after hardening—it can give rise to hardening cracks, grinding cracks, and flaking and spalling of the

case in service. We shall touch on this question of the carbon content of the case a little later.

Sodium carbonate and barium carbonate are the most popular energisers in use to-day. They are reasonably cheap and effective. A good compound (compound "A") can be made up of 5% by weight of sodium carbonate, 10% of barium carbonate, and 85% of hard wood charcoal. Now these must be intimately mixed to get maximum efficiency from the compound and to avoid patchy work which would be the inevitable result of badly distributed energiser. In other words every grain of charcoal should have its share of the energising salts. Ordinary mechanical mixing is surprisingly effective provided it is done very thoroughly. The sodium and barium carbonates should be in the form of very fine powder absolutely free from lumps and they should be intimately mixed together before adding them to the charcoal. If the final mixing is done just before the compound is put into use and there is no delay or considerable subsequent handling to cause a certain amount of separation (the energiser tending to settle to the bottom of the pile) all is well. When the compound so mixed has been through its first case-hardening heat, the energiser is found to be much more satisfactorily attached to the charcoal.

This mechanical mixing has obviously disadvantages and other methods of applying the energiser to the charcoal give better results although they increase the initial cost of the compound. A water process gives satisfaction—the energiser salts are dissolved and/or suspended in water which may contain a little organic adhesive or binder and the charcoal is treated with this liquid and subsequently dried. After drying every grain of charcoal will be found to be impregnated with the salts.

Other methods of applying the energisers employ oil or organic binders of one kind and another, and the products are given optimistic names and sold at high prices. The user must decide for himself which type of compound he will adopt, but the first two methods (plain mixing and water impregnation) will be found to give good compounds which will be free from serious variations and some other troubles in carburising which unfortunately distinguish many of the compounds on the market. A few remarks on these troubles will be appropriate here.

Compounds made up of bone black, saturated with hydro-carbon oil, give easy control of case depth and good support in the boxes for delicate parts, but they are expensive and slow—a much longer time is necessary to obtain a certain depth of case than would be required with the energised charcoal already described.

Other compounds contain poisonous ingredients such as cyanides for energising purposes and are dangerous to handle. Some cake in storage while others cake in the boxes during the carburising operation. Again others stick to the parts being carburised and, apart from the added work of removing the lumps, will frequently

cause pitting of the steel surface where adhesion took place. Others seem to produce a surge of gas when a certain temperature is reached and blow the lids off the boxes.

These troubles can all be avoided by using the simple charcoal compound energised with the barium and sodium carbonates and the rate of carburising will be found very satisfactory.

The cost of compound is naturally an important matter and the following points are worthy of note if compound is purchased ready for use :—

Compound is bought by weight, but boxes are packed by volume, and in buying particular note should be taken of the volume-weight ratio.

The amount of shrinkage which takes place in the carburising operation should also be noted. If the shrinkage is great, the top layer of parts may be wholly or partially exposed and soft spots will result. In addition, the amount of shrinkage (and loss of weight) is an indication of the frequency with which the same lot of compound may be used over again for carburising purposes.

This repeated use of compound is an important matter and the subject of much controversy which cannot even be summarised here. Let it suffice that in the author's opinion (confirmed by the methods adopted in many well-known plants) the best method of tackling the matter is to pack the carburising boxes with a compound mixture containing three parts of old compound to one of new. Compound "A" will give excellent results by this method, which is also satisfactory from an economic point of view.

It is not economical, however, to use the old compound over again immediately it has been removed from the previously carburised job. If it were mixed immediately with new compound in the above-mentioned ratio of three of old to one of new, it would certainly provide a carburising mixture, but the results obtained would not be nearly so satisfactory as they could be. Much better results are obtained by permitting the old compound to lie idle for a day or two—preferably in shallow trays or bins so that it is well spread out. In about three days it will be found to have recovered its carburising speed to a remarkable extent (probably by the absorption of carbon dioxide from the atmosphere) and on adding the requisite quantity of new compound a thoroughly good carburising mixture is obtained—better indeed than wholly new compound because it will be found to give more uniform results, less cementite in the case, and *will not shrink to any great extent.*

The hard wood charcoal used as a basis for the compound should not be of too fine a grain which results in dusty conditions in packing and too solid a pack in the boxes which is very slow to heat right through. Too large a grain on the other hand does not give adequate support to shafts, etc., which will distort badly if the charcoal settles unevenly in the boxes during the carburising process. A grain $\frac{1}{8}''$ to $\frac{1}{4}''$ in size and free from dust will be found satisfactory.

Boxes.

Carburising boxes cost a lot of money and here again the initial outlay is not the most important matter from an economic point of view.

Cast iron and cast steel boxes give poor results—scale and crack—and are not used now. Mild steel (boiler plate) boxes with welded seams are quite popular, but their life is short—up to 600 hours with feebly energised compounds, but after only 250 to 300 hours with highly energised compounds they are usually useless (burned through, distorted, and scaled away). Mild steel aluminised gives a longer life but with highly energised compounds operating at temperatures over 880°C. they do not last long enough to justify the extra cost of the aluminising process. Possibly the best all-round box is a cast alloy box of which the material is an alloy containing 65% nickel, 15% chromium, 20% iron. Several firms produce boxes of this type and over 5000 hours of life are guaranteed by the suppliers. Their initial cost is very high (over 2/- per lb.) but if their long length of life is confirmed by service test under your particular conditions, there is no doubt whatever that they are the most economical boxes at present available.

The dimensions of the boxes depend largely on the dimensions of the parts to be hardened. Very large parts may require one box for each part, in which case the shape of the box should be similar to the shape of the part, *e.g.* a long shaft can be carburised very well in a long tube 2″ larger in diameter. The important point is this—the smaller the boxes used the more uniform will be the results obtained.

As mentioned earlier, the thermal conductivity of case-hardening compounds is low and the centre of a large box is very long in attaining the carburising temperature, with the result that the case depth on parts lying near the outside of the box may differ greatly from that of parts lying near the centre, *e.g.* in a box 20″ × 10″ × 8″ small spindles $\frac{3}{8}$″ diameter near the sides of the box may show as much as 0·030″ case depth while those in the centre have only 0·015″. Such a state of affairs cannot be tolerated for delicate parts and other components which require a case depth controlled within narrow limits.

It is obvious, of course, that carburising small parts in very small boxes would entail a great deal of unnecessary labour and waste of furnace floor space. A good deal, therefore, depends on the judgment of the individual controlling the case-hardening operations, but there is a good rule to follow—for the satisfactory control of carburising small and medium-sized parts, such as those which form the bulk of case-hardening work in the automobile, aircraft, and machine-tool trades, one dimension of any rectangular case-hardening pot should not exceed 8″ and one other dimension

should not exceed 10″. A cylindrical box should not exceed 10″ in diameter and 10″ in height.

A very useful range of boxes would have the following dimensions :—

Length.	Breadth.	Depth.	Wall Thickness.
10″	8″	8″	$\frac{1}{4}$″
20″	8″	10″	$\frac{1}{4}$″
30″	8″	10″	$\frac{5}{16}$″
40″	8″	10″	$\frac{5}{16}$″
8″ dia.		12″	$\frac{1}{4}$″
9″ dia.		12″	$\frac{1}{4}$″

There is one other very important point about the size of the boxes; if they are too large they will cool much too slowly when removed from the furnace, which is not at all satisfactory from the metallurgical point of view. If it were not for the waste of compound entailed, parts would be extracted from the boxes immediately the latter had been withdrawn from the muffle, and allowed to cool freely in air. The best type of case would thereby be produced and it is therefore advisable to approach as nearly as possible to these ideal conditions—which rules out very large boxes. The point is this, when carburised parts are cooled very slowly from the carburising temperature the carbon gradient in the case does not retain its normal characteristics, of which we shall hear more anon, but instead it tends to be broken up into layers of differing carbon content which can become so sharply defined that flaking and spalling in subsequent hardening and/or grinding is almost inevitable. The cause of this peculiarity is somewhat obscure, but its effect can be so disquieting that every hardener must bear it in mind.

Note that the wall thicknesses of the boxes have been quoted above. These should be as small as experience permits and the above figures are for walls strengthened by diagonal ribs on their outer surfaces to reduce the tendency to distortion in service.

All case-hardening boxes should have well-fitting lids. A plain flat plate resting on a small ledge running round the inside of the top of the box will be found satisfactory if cut to the proper size. It should be borne in mind that the more thoroughly the box is sealed the better, and the less fireclay it is necessary to use for the purpose, the less is one concerned about it cracking and allowing gases to escape and less care need be exercised to see that it does not contaminate the compound when the boxes are being unpacked. Small pieces of fireclay mixed in the compound may rest on an important surface the next time the compound is used and soft spots will result.

The advisability of thoroughly sealing the boxes arises from the fact that the higher the pressure attained by the carburising gases inside the box, the faster will they do their work. A recently patented case-hardening process developed in Germany gives amazing results by the use of this important fact.

The fire-clay is simply made into a stiff paste with water and plastered round the edges of the lid. No time to dry is required—the boxes can be placed in the furnace immediately the sealing is completed.

Another point about the sealing of the boxes is this. Compound gets burned away if air has a certain amount of access to it during carburising, and during the emptying process it may be found necessary in consequence to throw away two inches or more of ash from the top of a box with a broken seal. Such ash, if left in the compound, would reduce the efficiency of the compound for subsequent use and represents a serious waste of good material.

If other types of lid are used the amount of fireclay needed for sealing may be reduced or eliminated entirely, *e.g.* a flanged lid which covers the case-hardening box completely and neatly will be found to give a reasonably good seal without using fire-clay, provided the section of the lid is heavy enough to keep it solidly down on the edges of the box and to maintain its shape through successive heats. It should be borne in mind, however, that the amount of heating time which can be lost by the use of heavy lids, etc., is considerable. For example, if your boxes (complete with lids) weigh 70 lbs. when, by judicious reduction of wall-thickness, etc., you could have well-designed boxes of similar general dimensions weighing only 50 lbs. to do the work, and a particular furnace takes three carburising loads in the twenty-four hour day with 12 boxes in a load, you are, in effect, wasting in one day the heat required to raise 720 lbs. of metal from atmospheric temperature to 900°C. or thereby—a serious matter over a period with several furnaces similarly handicapped.

Furnaces.

A great variety of furnaces is at the disposal of the engineer setting up a case-hardening shop in his works. His choice depends on cost and availability of fuel, and on the bulk and uniformity of work he has to tackle. As far as fuel is concerned, from the point of view of carburising efficiency there is little to choose between oil, gas and pulverised coal. Electricity, however, is still a doubtful proposition for this type of work, as the "bulk" of heat available in the ordinary electric muffle is not great, and the load may be much longer in reaching carburising temperature. Local conditions must decide which of the other fuels is chosen.

As far as the furnace construction is concerned the ordinary single door muffle is still the most popular for carburising purposes. The door must be a good fit and kept good. If the quantity of repetition work justifies it, then conveyor furnaces of one kind or another may be installed with advantage. These are so controlled that the boxes pass through the heating range and then have the proper length of "soaking" time before they reach the discharge end of the conveyor (whether it be a rolling hearth or moving hearth). The important points are these :—

(*a*) There should be very heavy insulation because (1) an even temperature all over the floor is then more easily attained and maintained, (2) the latent heat in the furnace walls and floor can be of great assistance in heating up a charge steadily and quickly, and (3) heavy insulation means low fuel consumption to maintain steady temperature for a long period.

(*b*) The burners must be accessible for cleaning and adjustment, which should be attended to once a day.

(*c*) The atmosphere over the hearth should be incandescent, *i.e.*, no flames actually in the furnace to cause local fluctuation of temperature.

(*d*) The flue arrangements should be such that the hearth is well heated from below, so that the work does not depend entirely on heat flowing from top and sides.

(*e*) The fuel and air controls should permit of a very fine adjustment. Far too many furnaces have their temperatures increased or decreased 50°C. or more by the smallest movements the operator can make on his control lever and yet he is expected to keep within plus or minus 5°C. of the specified temperature.

(*f*) At least one permanent pyrometer should be attached to each furnace—two or more may be required to give satisfactory control of large or conveyor furnaces. The pyrometer stems should project at least 6″ into the furnace atmosphere. The point should be close to the work but clear of it and clear also of stray flames which would cause false readings to be obtained.

Pyrometers.

All pack-hardening work must be pyrometrically controlled and the author refuses to recognise any other known method of checking temperature as reliable. A complicated system is not essential and the equipment is not nearly so costly as the layman sometimes imagines. Base metal thermo-couples give good service and several can be connected to one wall or desk indicator so that the temperature of a number of furnaces can be read off the same indicator by the simple operation of a special switch. Recording instruments are valuable for carburising work because of the long period of heating and soaking. The recorder gives a complete temperature-time curve for each charge and is therefore of great assistance to shop superintendents and metallurgists responsible for checking the work of the heat-treatment department.

In medium-sized or large plants automatic control of temperature can be installed with great advantage irrespective of the fuel used, provided it be gas, oil, or electricity.

A standard rare metal thermo-couple or platinum resistance thermometer should be used at least twice a week to check the readings obtained on the permanent pyrometers attached to the furnaces. This should be done by inserting the "poker" into the furnace alongside the fixed pyrometer. A special inlet in the furnace wall or roof should be provided for the purpose. The standard instrument may also be used with advantage in determining the magnitude of the almost inevitable variations in temperature over the floor area of a large furnace. When the extent of these variations can be measured, however, it assists greatly in evaluating the remedies tried out.

In consultation with reliable instrument makers, the standard pyrometer should itself be checked at agreed intervals.

Selective Hardening.

A description of the equipment required for case-hardening operations would not be complete without some reference to the copper plating vats and their significance.

If it is either desirable or necessary to keep certain portions of the surface of a case-hardened part soft, there are several ways in which this can be done.

The most certain method is covered by the phrase "machining after carburising." As the reader is aware the parts are still comparatively soft when removed from the carburising boxes and can be machined in the ordinary way. If, therefore, in the original machining operations surplus material is left on the surfaces which must be soft, and this surplus (which must obviously slightly exceed in thickness the case depth aimed at) is removed after the carburising operation, the said surfaces cannot harden in the subsequent heat-treatment operations. This method is, however, rather costly and sometimes inconvenient and the extra handling alone requires careful planning to make it an economic method for ordinary production work.

Differential heat-treatment after carburising has been used as a method of keeping, say, one end of a shaft soft by simply taking care that only the end which is to be hard is immersed in the quenching medium, but this method has little to commend it except for a few unimportant parts and we shall pass on.

The reader will immediately appreciate the possibilities of the application to the surfaces to be kept soft of some shielding material which will prevent the gases from affecting these surfaces during the carburising operation. Various clays, cements, water glass and asbestos mixtures, and patented "anti-carburisers" of putty-like consistency, are recommended for this purpose, but in spite of their theoretical possibilities, and the high prices at which some of them are retailed, none of them gives any better results than are obtainable with $\frac{1}{4}$" thick coating of blue clay (which need not be

dried before the parts are packed in the boxes). In fact, some of these anti-carburisers which contain ferric-oxide and other oxidising agents to counteract the carbon monoxide in the carburising boxes, are most undesirable because they impair the compound seriously and the presence of little pieces which may be unavoidably lost in the compound when the boxes are unpacked will cause soft spots in the next jobs. As far as the blue clay is concerned, however, do not imagine for a moment that it gives really satisfactory results. It simply reduces the case depth considerably where applied if applied firmly and carefully, but it does not keep the surface really soft and is useful only when there is no objection to a hard surface as long as the case at that point is not deep. For keeping the case on coarse screw threads within reasonable bounds and plugging small-tapped holes, etc., it can be quite useful.

Copper plating remains deservedly the most popular method of keeping certain areas soft when a part is being case-hardened. It can be applied scientifically and with precision and its cost is not so great as is sometimes feared. In addition, if properly done, it gives excellent results and the surfaces so protected will be found quite free from case so that after the completion of the hardening process, they can be drilled or otherwise machined if necessary.

The copper plating process should be carried out as follows :— The parts, if not already machined all over, should be pickled to remove scale from the black surfaces, rinsed, thoroughly scoured with pumice powder, and rinsed again in clean water. If machined all over before arrival in the plating shop, they must be washed in hot alkali (say, 10 per cent. soda), rinsed, thoroughly scoured with pumice powder and wire brushes, and well rinsed again in clean water. Subsequent contact with the operator's hands is to be avoided as the inevitable smear of perspiration is quite sufficient to cause poor adhesion of the copper coating.

Those surfaces which are not to be plated must then be covered with a protective enamel. Copal varnish (coloured with ochre) subsequently stoved is quite good, but quick drying cellulose lacquers are now available and give better results, especially during extra long immersions in the plating vat when a heavy coat of copper is required.

After enamelling, the parts are made the cathodes (the anodes being hot-rolled pure copper plates) in a "cyanide" copper plating solution of the following composition :—

Copper cyanide,	10-gms./litre.
Potassium cyanide,	10-gms./litre.

This operates best when the solution is kept at a temperature of approximately 120 degrees F. The voltage used should range from 2 to 5, as the distance between the anodes and the work varies between 3 inches and 6 inches. The current density should be $2\frac{1}{2}$ to 4 amps per sq. foot.

The solution must be kept in order by checking the cyanide content once a week at least by a simple laboratory test (which does not need a laboratory or a chemist to carry it out) and adding the necessary quantity of sodium cyanide. The "free cyanide" concentration so controlled is a very important matter. A lack of free cyanide causes the appearance of a heavy brownish-black deposit on the anodes, and the slowing up of the plating process. An excess of free cyanide, on the other hand, makes the anodes very "bright," and stops the deposition of copper on the work. It is well worthy of note at this point that it is never necessary to add the theoretical amount of sodium cyanide when these weekly tests are taken, and it is, in fact, wasteful to do so. About 75 per cent. of the theoretical amount will be found adequate. It should never be necessary to add copper salts to the solution as some people do when there is the slightest indication that the plating is not of the usual high quality. These copper salts are expensive and quite unnecessary after the original making up of the solution. In fact, it will be found that the copper cyanide content will increase gradually as the bath is used and may ultimately range between 25 and 35 grammes/litre. About once a year a bath that is constantly in use usually requires the complete scrapping of the solution because of the accumulation of dirt and inert salts (carbonates, etc.).

A plain iron tank is the best container for the cyanide plating solution.

About a minute and a half in this solution is sufficient to give that foundation of adherent copper without which the subsequent heavy plating in the "acid-copper" vat would not give satisfactory results.

When the parts are removed from the cyanide plating solution they should be dipped smartly in clean cold water and then plunged into the acid copper vat for the completion of the plating process. Here again the parts are the cathodes (copper anodes) and the solution has the following composition :—

Copper Sulphate Crystals ($CuSO_4$ .5 H_2O),	2 lbs. 2 ozs.
Potash Alum, ...	2 ozs.
Conc. Sulphuric Acid, ...	5 ozs.
Water, ...	1 gall.

This solution should be worked cold, but the temperature should not be allowed to fall below 65 degrees F. The voltage should be $2\frac{1}{2}$ to $3\frac{1}{2}$ and the current density from 15 to 40 amps. per sq. foot, the latter depending upon the shape of the work which naturally governs the distance between the work and the anodes. It will, of course, be appreciated by the reader that the higher the current density used the shorter will be the time necessary to get a certain thickness of copper deposited, but the low current densities give the best deposits.

As far as the composition of the solution is concerned, the copper sulphate and sulphuric acid contents both tend to fall with use and

as the above figures represent the most efficient concentration, it is necessary to estimate both these constituents once every two weeks, and subsequently add the appropriate amounts of each to restore the solution.

If the bath is operated carefully, the life of the solution will normally depend on the speed at which iron salts accumulate in it. These salts seriously affect the conductivity of the solution and the quality of the deposit, but with reasonable care the solution should last for many years. The most important point to bear in mind in this connection is this: *before articles are suspended in the solution the current must be switched on*, otherwise the acid in the solution dissolves a certain amount of iron from the exposed steel surfaces and the quantity of iron salts can become very serious in a very few weeks. A check on this accumulation of iron is therefore advisable about every three months.

A wooden tank unlined or rubber lined is the best container for the acid copper plating solution.

The thickness of copper coating required depends on the length of time the parts will be exposed to the carburising gases. 0·004 inches are necessary to resist very long carburising periods of say, 24 hours, but 0·002 inches are adequate up to 14 hours, and for normal times of 4 to 10 hours 0·0015 inches are about right.

About two hours in the acid copper vat are necessary to obtain the last thickness mentioned and when the parts are removed from this solution they are rinsed in cold water. A dip in hot water to assist drying, and drying off, will make them ready for packing in the carburising boxes if a cellulose enamel has been used to stop-off the copper from the surfaces which must be hard. In other words, there is no need to remove cellulose enamel which is practically ashless and does not affect the carburising process or the compound. Copal varnish and other stopping-off paints must be removed with caustic alkali before the parts are packed.

If the parts are properly cleaned the copper coating will be found O.K., but do not imagine that copper will lovingly embrace the most repulsive of black, oily or scaly surfaces.

Before we pass on to give some consideration to the types of steel used, it is well worth emphasising that when the parts are being packed in the boxes, the latter should be shaken at intervals to ensure that the compound fills the spaces properly and supports the parts adequately, but on the other hand it must not be rammed tight. Carburising compounds are poor conductors of heat and a box rammed really tight will be many hours longer in reaching carburising temperature in its very centre than would be the case with a similar size of box packed reasonably. 1½ inches of compound on the bottom of the box, 1-inch all round the parts, and 2 inches on the top of the box (this last to allow for the slight shrinkage which cannot be entirely avoided) will give good results.

When heavy boxes and work are being handled in considerable quantity, it may be found advisable to instal some mechanical method of agitating the packing table in order to eliminate shaking the boxes manually as suggested above.

The reader will appreciate that the spacing of boxes in the furnace is rather important in order to obtain reasonably even heating as their temperature is raised. The most suitable spacing naturally depends on their size—small boxes should be three to four inches apart and large boxes six to eight inches apart. In addition, long boxes should be placed at right angles to the sources of heat, which will be the side flues in most single door muffles. None of the boxes should be less than six inches from the back and side walls of the furnace or less than a foot from the door.

The timing of the carburising period is the only other point about the mechanics of the job which requires attention at this stage.

Once the boxes have attained carburising temperature throughout, the speed of carburising is a definite value dependent on the composition of the steel, the type of compound, and the temperature. These three things can vary so much, however, that the attempts which misguided authors sometimes make to provide their readers with nice tables or graphs of carburising speed are of very doubtful value and can indeed be horribly misleading. In any event, they give times which begin when the job has reached carburising temperature, and who in an ordinary heat-treatment shop knows when that is? The blunt truth is that the only satisfactory method of timing carburised jobs measures the period from the time when the boxes are charged into the furnace and depends for its accuracy on the experience of the man in charge supported or replaced by test pieces withdrawn from the boxes at appropriate times. The appropriate times depend on the variables already mentioned plus the other obvious variables which render timing difficult by any other method, viz., size of boxes, thickness of boxes, grain size of compound, tightness of packing, and original temperature of furnace. The variables mentioned earlier govern the speed of carburising once the carburising temperature has been reached, and they are outwith the operator's control. These other variables mentioned now, govern the rate at which the parts heat up to the carburising temperature and are controllable to a certain extent. The original temperature of the furnace, however, can be made more or less standard—80 degrees above the carburising temperature is a good original furnace temperature. The boxes will bring it down sufficiently, long before any of the parts get overheated.

The test pieces may be actual parts if these are not expensive. In other cases round bars of the same material of a diameter similar to the ruling or critical thickness of the parts should be used. Four inches of length will be found adequate. They can have a piece of wire attached to make location and extraction easy. The important test piece should be in the centre of the centre box or as

nearly so as convenient. After a very little experience the operator will not find more than two test pieces necessary. The first should be extracted, quenched, and broken, when he thinks the specified case depth will have been obtained. The second will confirm his judgment if he finds it necessary to extend the time in the furnace as a result of his examination of the first.

The Case-Hardening Steels and their Treatment.

All forgings for case-hardening purposes should be normalised before machining in order to relieve stresses. If this is not done, the stresses will be relieved during the carburising operation and the resultant distortion may cause endless trouble. In the event of extra heavy machining operations taking place, or in cases where distortion must be reduced to an absolute minimum, it will be found advantageous to introduce the normalising operation after the rough cuts have been taken. There must, however, be machining operations between the normalising and the carburising in order to true the part up, otherwise the normalising is useless. Remember in this connection that the normalising operation is of little value from the point of view of steel structure and properties when a carburising operation has subsequently to be performed. The latter obliterates completely the effect of the normalising from a metallurgical point of view.

Mild steel with no alloy content is the most commonly used and should therefore be considered first. B.S.I. specification No. 2 S 14 covers the desirable chemical composition adequately as follows :—

Carbon,	...	0·10 — 0·18%
Silicon,	...	not over 0·30%
Manganese,	...	,, ,, 0·90%
Sulphur,	...	,, ,, 0·05%
Phosphorus,	...	,, ,, 0·05%

For work of a very delicate nature the maximum carbon content should be 0·13% and the manganese should lie between the limits 0·35—0·55%.

The impurities in steel for case-hardening purposes are even more undesirable than in other steels, and the reader is referred to the author's pamphlet "The Heat Treatment of Steel," and to the further comments in this one under "Inspection." It is notable, however, that manganese promotes grain growth during the carburising operation and is therefore not used for alloying case-hardening steels, and should never exceed the limits quoted in the specifications given in these pages.

Parts manufactured from 2 S 14 steel should be carburised at a temperature of 900 to 920 degrees C. Lower temperatures are uneconomically slow and give no better result, while higher temperatures are not recommended because in hastening the carburising

process they cause the case to be super-saturated with carbon, thus creating cementite with its undesirable features mentioned early in the paper, and, in addition, the grain growth of both case and core is excessive and difficult to remove in subsequent heat-treatment.

When the parts are removed from the carburising boxes they are, as we know, still soft on the surface, and as a result of the long soak at the appropriate carburising temperature, the grain of both case and core is large. It is therefore necessary to give them the following heat-treatment :—

Raise to 900 degrees C., soak 10 minutes, and quench in water.
Then raise to 780 degrees C., do not soak, quench again in water.

The first of these re-heat-treatment processes refines the low carbon core of the material (900 degrees C., being just nicely above the critical range of low carbon steel which will not "harden" in the ordinary sense) thereby increasing its tensile strength and impact value. The second heat-treatment refines and hardens the case (780 degrees C., being the hardening temperature of a 1 per cent. carbon steel) without affecting the core much, because 780 degrees C. is well below the upper critical temperature of the low carbon material.

After this treatment the following results should be obtained on $1\frac{1}{8}$ inches diameter bars :—

Maximum stress,	...	not less than 32 tons sq. in.
Elongation, ...	...	,, ,, 20%
Reduction of area,		,, ,, 50%
Brinell (of core),	...	140 — 200.
Case-hardness,	...	not less than 800 diamond hardness.

The author mentions $1\frac{1}{8}$" diameter bars advisedly because the remarks he makes on the effect of mass in his previous pamphlet apply with equal force to the case-hardening steels and should be borne constantly in mind.

The case-hardness quoted here will be understood more easily when the points stressed under "Inspection" are studied by the reader.

If case-hardness only is required and the core of the parts need be neither strong nor tough, the first re-heat-treatment can be omitted entirely. In fact if some reduction of case-hardness and quality (grain refinement) can be permitted, the parts may be quenched in water direct from the carburising boxes by opening and emptying these with as little delay as may be after removal from the furnaces, so that when the parts strike the water they are still at some temperature well over 760 degrees C. For important work, neither of these modifications can be tolerated. The second modification, contrary to popular belief, does not refine the core (it

preserves the coarse "as carburised" structure) and may, in any event, prove uneconomic unless steps are taken to save the compound by catching it in such a receptacle that it can be covered immediately to prevent free contact with the atmosphere. If this is not done, quenching parts direct from the boxes at or near carburising temperature destroys the compound entirely and under no circumstances must it be mixed with good stuff. Even if the special precautions mentioned are adopted, the compound so saved should not be subsequently used for first-class work.

During these re-heat-treatment processes, the furnace atmosphere should be neutral or very slightly oxidising. A markedly reducing atmosphere causes de-carburisation of the steel surface without the formation of much scale and the optimum hardness is not obtained. This type of decarburisation is very undesirable because it is not removed by sand blasting or similar finishing operations. A strongly oxidising atmosphere, on the other hand, causes the formation of heavy scale and some decarburisation. Apart from the roughening effect on the surface of the work, the heavy scale will prevent sufficiently rapid cooling of the surface in the quenching operation and soft patches will remain when the scale is blasted away. A slightly oxidising atmosphere is the ideal and forms a thin layer of scale which protects the surface from further decarburisation and yet does not interfere with the quenching.

The first or "high heat" for refining the core is, of course, the more troublesome from this point of view. When the furnace atmosphere is difficult to control, it may be found advisable to sand blast the parts between the first and second heats in order to ensure that maximum hardness will be produced by the latter.

The quenching medium also requires some attention if the best results are to be obtained. The water should be cold (continuous inlet and overflow if possible), clean (oil film on the surface is specially to be avoided), at least 5-ft. deep, and free from aeration. Still greater depth renders the swilling out of all but heavy section parts quite unnecessary. The freedom from air bubbles avoids a sure source of soft spots.

During heating up in the heat-treatment furnaces, the parts should be moved when the appropriate temperature is nearly attained. The rolling over of cylindrical parts and the moving of others removes any tendency for their undersides to be "dull."

Town gas-fired furnaces will be found very suitable for this type of work because of their rapid response to "opening the throttle," good atmosphere control, and ease whereby even heating can be obtained by the careful adjustment of the multiple burner arrangement which distinguishes most of them.

In the author's pamphlet on the "Heat-Treatment of Steel," the effect of additions of nickel, chromium and molybdenum on carbon steels was described. The remarks apply with equal force to steels for case-hardening purposes and the effects are essentially the same.

It is therefore not surprising to find that there is a useful range of alloy case-hardening steels. In fact, the addition of alloys is the only method of obtaining high tensile case-hardening steels. Increasing the carbon content would not remove the necessity to quench in water in order to get glass-hardness on the surface, and the medium or high carbon core would be intensely brittle and prone to cracks.

The most popular alloy case-hardening steels are covered by standard specifications and their compositions, treatments, and properties are given in Table 1. The plain carbon case-hardening steel already described (case-hardening mild steel, as it is often called) is included for comparison.

The lower carburising temperatures recommended for the alloy steels arise from their greater sensitivity to over-heating and the consequent difficulty of obtaining adequate toughness if the recommended temperatures are much exceeded.

The alloy steels carburise more slowly than case-hardening mild steel. They take from 10 per cent, to 25 per cent. longer to attain the same depth of case, and the lower carburising temperatures increase the necessary time still further, but no difficulty need be anticipated in gauging the period after a little experience provided test pieces are broken as indicated earlier in these notes.

The fall in the attainable surface hardness as the alloy content of case-hardening steels is increased is an interesting feature. The fall is not due to the change to oil-quenching, but is simply a fact that has to be accepted as inherent. For example, if S.82 steel is water-quenched in the second heat, it is found to be a good deal softer on the surface than if oil-quenched. This seems extraordinary but has a simple explanation. As a result of the high alloy content, it is easy to retain the solid solution state by quenching—so easy, in fact, that while Martensite (giving maximum hardness) is formed by quenching in oil, a certain amount of austenite is retained by the water-quench and lower hardness figures are obtained. The presence of the chromium accounts for the high surface hardness of the nickel-chromium steels.

A single heat-treatment process after carburising is often advocated for nickel case-hardening steels and the results obtainable from 5 per cent. nickel steel under these conditions are given in the table. The elimination of the first heat should never be attempted when the nickel content is under 3·6 per cent., but with higher nickel contents a definite saving can be effected in this way, and the results normally remain good. Such departures from recommended practice are to be discouraged, however, if there is any doubt about the steel or its previous treatment.

The hardnesses of these steels on the surface after carburising are of importance if any machining operations are to be carried out at that stage. The normal figures obtained are :—

Steel.	*Diamond Hardness.*
Nickel Chromium C.H. Steel, Spec. S.82,	450 - 520
5% Nickel Steel, Specs. S.67 and S.83,	340 - 430
3% Nickel C.H. Steel, Spec. 3 S.15, ...	320 - 420
C.H. Mild Steel, Spec. 2 S.14, ...	250 - 320

The high figures obtained because of the pronounced air-hardening qualities of the carburised surfaces of the highly alloyed steels renders machining of these difficult if not impossible, and in order to carry out such machining operations easily, it will be found necessary to anneal the parts after carburising. For all the steels mentioned, an annealing temperature of 670 degrees C. is about right, and the parts should be held at that temperature for a period of thirty minutes before withdrawal from the furnace to be cooled freely in air.

If this annealing operation is properly done the subsequent hardness figures should not exceed those quoted below :—

Steel.	*Diamond Hardness.*
S.82, ...	350 max.
S.67 and S.83, ...	335 ,,
3 S.15, ...	320 ,,

2 S.14—No need to anneal.

The actual figures depend largely on the dimensions of the parts and the rate of cooling.

The reader will have observed in Table I. a column devoted to "Tempering Temperature," and has no doubt wondered at this treatment being applied to case-hardened steels. However, he will no doubt have observed also that the tempering temperatures quoted are very low, which differentiates them from the tempering temperatures used in heat treating ordinary steels.

The tempering operation we are discussing now is carried out after the case-hardening process is complete and the parts are on the point of despatch to the machine shop for finishing operations. It is optional, but strongly recommended for case-hardening mild steels and the nickel case-hardening steels, and should be a routine operation for the nickel chromium types—the use of these last for certain parts is sufficient indication that the said parts are required to have first-class properties and the tempering operation just completes the job nicely for the following reasons :—

(*a*) It toughens the case without affecting the core to any appreciable extent.

(*b*) It strengthens the bond between case and core.

(*c*) It has a most marked effect in reducing any tendency for the case to develop cracks in grinding operations.

(*d*) It removes all normal hardening stresses.

The author desires to emphasise that although the tempering is quoted as optional for case-hardening mild steel and the nickel steels, it can be, and often is, used with great advantage to these for the reasons given. For example, the tendency for flat surfaces to crack in grinding operations (due to the difficulty of getting an adequate quantity of coolant between the surface of the grindstone and the surface of the parts) can be reduced very greatly, and case-hardened surfaces which have to withstand a certain amount of pounding in service will resist rupture longer if tempered as indicated.

The tempering temperatures quoted are maxima and the actual temperature used must depend on the idea behind the application of the tempering operation, because, although the maximum temperatures quoted are low, they are nevertheless sufficiently high to soften the case-hardened surfaces appreciably and the extent of that softening must be borne in mind when fixing the temperature. 100 degrees C. softens the surface very, very slightly—the difference being not measurable by ordinary methods. 140 degrees C. is the safest temperature to use for it is effective and, although the surface hardness is measurably affected, the actual fall is not serious.

The following figures illustrate the effect of tempering temperature on the case-hardness of a typical nickel-chromium steel to B.S. Specification S.82 ($1\frac{1}{8}$" diameter bars).

	Diamond Hardness.
Refined 840 degs. C., hardened 780 degs. C. in oil,	760 - 780
As above, then tempered at 100 degs. C.,	742 - 770
As above, then tempered at 140 degs. C.,	735 - 760
As above, then tempered at 200 degs. C.,	690 - 715

The tempering operation is, in the author's opinion, best carried out in a liquid bath of oil or grease and the time *at temperature* should be at least one hour, but longer is required for heavy parts. Low temperature electric furnaces with forced air circulation are also good for this operation.

It is interesting to note that the tempering may actually cause an increase of surface hardness if the quenching of the parts in the second or "low heat" was particularly drastic, *e.g.* when carburised S.82 steel has been water-quenched and some austenite is retained in the case as indicated earlier. In such instances the low temperature tempering decomposes the austenite, and martensite with its maximum hardness characteristics is formed in its place.

Before we pass on to the inspection of case-hardened work, some attention might well be paid to Table 2 which gives a typical example of the effect of mass on the core properties of a case-hardening steel.

After case-hardening, the parts should be shot-blasted to remove all scale. They should then be subjected to the low temperature tempering treatment just discussed, washed, and passed out for inspection.

TABLE 2.

The Effect of Mass on a 5% Nickel Case-Hardening Steel.

Diameter of Bar.	Tensile Strength in Tons/Sq. In.	Elongation per cent.	Brinell Hardness.	Izod Ft./Lbs.
$\frac{5}{8}$ ins.	88	17	415	30
$1\frac{1}{8}$ ins.	80	18	364	35
$2\frac{1}{4}$ ins.	61	21	277	52

COMPOSITION—Carbon 0·16%, Nickel 5·90%, Manganese ·45%, Chromium 0·19%.

HEAT TREATMENT—Carburised 880°C., Refined 830°C. (Water Quenched), Hardened 760°C. (Water Quenched).

Inspection.

Please note that the shot-blasting of case-hardened parts is of the greatest possible value to the inspector. Soft spots or patches will show up as dark grey blotches on the silvery-blasted surface and provide useful clues and information to a watchful and intelligent man.

> Thorough blasting (in other words, more than just the removal of scale) which leaves the parts silvery clean and free from dust, is also of great value in keeping grinding wheels clean, with the result that a tendency to cracking in grinding operations may be eliminated in certain instances by improving the blasting, but that is by the way.

The inspector's first job is to examine visually the parts for apparently soft patches, confirm the softness by actual hardness tests, and reject the unsatisfactory specimens.

And now for the actual hardness tests.

For this purpose the inspector's most useful instrument is a thin, flat, chrome-cut, ward file which will grip all but the glass-hard surface coveted by hardeners. Instrument makers may smile in superior fashion at this exaltation of the humble tool in question, but the fact nevertheless remains that a good file in the hands of an experienced inspector will tell nearly the whole story—enough anyway to make it rank with the scientific testing machines as an important and essential instrument for this type of work.

The only part of the story the file does not tell is this. Skin hardness (even of the "glassiest") is seldom alone sufficient and that other important property, the depth of hardness, is unfortunately beyond the scope of the file as a testing instrument. To confirm that the depth of hardness is adequate, an indentation type of hardness tester is required.

The Brinell form of ball indenter is useless for case-hardened work. The impression made is so small and the distortion of the ball causes so much further inaccuracy that this method is no longer in use. In fact, the ordinary Brinell test is not to be relied upon for the hardness testing of any materials of greater than 350 Brinell hardness, unless a specially hard Tungsten carbide ball is used. Even then, readings over 500 cease to be true Brinell readings, and for such tests a machine using a 136° pyramidal diamond indenter should be employed.

The Vickers machine and its relative, the Firth Hardometer, are the best known of this type, and provide us with an accurate and consistently reliable method of measuring hardness. For case-hardened parts their use is invaluable.

The principle of these and similar machines is simply this. A pyramidal diamond indenter (with an included angle of 136 degrees) is pressed into the surface being tested by the application of a known load. The square impression so formed is measured across its diagonals by means of a suitable microscope complete with scale (the mean of the two readings being taken when slight variations are found) and the true Brinell reading (as distinct from the figure of doubtful value obtained by the ordinary Brinell machine) is subsequently read off from tables provided by the suppliers of the machines (facsimiles of some of these are included at the end of this pamphlet). The indentation is so small that the parts are not permanently damaged by the test.

As already suggested, the diamond hardness figures and the ordinary Brinell figures are identical up to 350 Brinell. Beyond that, the diamond hardness figures should be regarded as the true Brinell figures and as standard. The Standard Brinell table is reproduced here (Table 5). Reference may be made to British Standard Specification No. 427 for diamond hardness tables.

Now a thin case a few thousandths of an inch in depth will be glass hard to a file test if the heat treatment after carburising has been right, but it will be crushed by the diamond indenter of either of these hardness testing machines and a comparatively low reading will be obtained by the latter method unless a very light load is used—which raises the question of loading.

Both the pyramidal diamond machines mentioned are obtainable with different loading arrangements, as they are used for a variety of purposes from testing the hardness of razor blades with a 5 k.g.m. load to testing the same property of chilled rolls with a 120 k.g.m. load, which is the maximum obtainable. Tables are supplied to suit the particular loads and the results obtained with one load are comparable with those obtained with another.

For case-hardened work the 120 k.g.m. load is recommended by the author for deep cases and will give the true hardness of the surface for all case depths in excess of 0·012 inches if the parts are pack-hardened (cyanide hardened parts have a steeper hardness

gradient through the case and 0·018 inches case depth is the minimum for reliable readings on these using a 120 k.g.m. load machine).

For cases 0·005 inches to 0·012 inches in depth a 30 k.g.m. load machine is admirable. For cases under 0·005 inches the file test is good enough.

The 30 k.g.m. load or a lighter one would give accurate readings of the surface hardness of parts with deep cases, but the heavier load has the advantage of being a more severe test in that it gives some indication of the minimum case depth. The author mentioned that the main disadvantage of the file was its inability to do more than check the hardness of the skin (although that is quite a lot to be going on with) and while the diamond hardness testing machines cannot give an accurate estimate of the case depth they can, by judicious use of the different loads, be used to make certain that the case depth exceeds a certain minimum with all the satisfaction that accrues from that certainty.

Provided the load used does not exceed that which the case depth can support, the following hardness figures should be obtained on the surface of case-hardened parts whether before or after grinding :—

Steel.	*Diamond Hardness.*
C.H. Mild Steel, Spec. 2 S.14, ...	850 min.
3% Nickel C.H. Steel, Spec. 3 S.15, ...	750 ,,
5% Nickel C.H. Steel, Spec. S.67, ...	700 ,,
Nickel Chromium C.H. Steel, Spec. S.82,	730 ,,

For other figures, see Table I.

The minimum for case-hardened mild steel parts is, however, usually regarded as 800, but the above figure is normally attainable and should stand for all important work.

Before we discuss more inspection points, other two hardness testing instruments must be mentioned. These are the Rockwell instrument and the Scleroscope.

The Rockwell hardness tester is a very useful instrument because it is rapid in operation compared with the two diamond hardness testing machines already described.

A diamond indenter (in this case a diamond cone with an angle of 120 degrees) is used in the Rockwell method also, but the hardness figure is obtained in an interesting way. The indenter is pressed into the specimen first of all by means of a known light load (10 kilogrammes) and the attached clock gauge is set at zero. The full load (150 kilogrammes) is then applied through a system of levers and the clock gauge registers the resultant increase in depth of penetration of the indenter. The hardness scale is an empirical one and has comparative value only, but as the Rockwell instrument has been widely used in this country and America for many years, the hardness figures it normally gives for all sorts of steels are well known and limits can be fixed quite easily for the class of work requiring test. There is, of course, no direct relation between the

Rockwell hardness figures and standard Brinell figures, but in the hope that it will prove useful for reference the author provides at the end of this paper Table 6 showing which Rockwell figures are usually regarded as corresponding to certain Brinell figures. Because the Rockwell machine gives direct readings on a clock gauge and no microscope manipulation is necessary, it is, as has been said, more rapid in operation and can be of great value in routine checking of the hardness of large batches of work. It is open to the usual objections associated with spring type gauges and obviously the accuracy of its readings can be seriously affected by scale or dirt between the part being tested and the anvil on which it rests. The dirt is crushed when the full load is applied and increases considerably the apparent penetration. Small particles can cause a large percentage error because the penetration is, in any event, a very small amount. Exercising reasonable care in the operation of this instrument, however, and checking it frequently on standard test pieces of known hardness (and also checking it against a Vickers or Firth machine) can make it a useful tool for routine work.

The Scleroscope is a popular instrument which is supposed to measure surface hardness by the height of the rebound of a diamond-tipped piston in a graduated glass tube when the piston is allowed to fall on the surface being tested, but the author cannot honestly say it has any real uses in testing case-hardened parts. It cannot tell anything the file and shot blasting might overlook. It may be of value for disclosing differences in the hardnesses of fairly hard materials which are gripped by a file and yet must be thoroughly tested over an area—a laborious task with indentation type instruments.

It may be mentioned here that the three indentation type diamond hardness testing machines described are usually supplied with hard steel ball indenters as well. The Rockwell ball is seldom used for case-hardened work. The Firth and Vickers machines become baby Brinell machines when the ball is substituted for the diamond and give true Brinell readings provided the relation of the diameter of the ball to the load imposed on it is in accord with B.S.I. Specification 240. They can be very useful in testing the Brinell hardness of small sections of material which would not support the standard Brinell test but, of course, for Brinell hardnesses over 350 the diamond indenter should be used.

It is under the heading of "Inspection" that the points about steel quality can most conveniently be stressed, because the effects of impurities, etc., are very obvious to the metallurgist who may have to come to the assistance of the inspector and the hardener when poor results are obtained. The steel must be free from heavy slag inclusions and other segregations, and from dissolved oxides. All these give rise to soft spots and the segregations may, in addition, cause actual cracks and flaking of the case. The dissolved oxides can result in rapid loss of hardness in grinding or under other con-

ditions which cause slight rise in surface temperature. All these defects are the result of unsatisfactory methods of steel manufacture and are absent in really good quality material.

Acid open-hearth steel is best for case-hardening, but basic steels give satisfactory results if the sulphur and phosphorus contents are kept low.

In addition to the surface hardness of case-hardened parts, we want to know in most instances the case depth and the condition of the core. Some indication of the former will have been obtained from the test bars broken before the boxes were withdrawn from the carburising furnaces, but where large or important batches are involved and economic considerations permit, it will be advisable to scrap one or more parts to measure the depth on these. This can well be done by sawing the part partially through and then breaking finally with a few hammer blows. The case can be measured by the use of a small microscope with an inch or millimetre scale attached—the Brinell microscope is useful for the purpose. When in doubt, the section should be carefully polished and then etched in a dilute solution of nitric acid, whereupon the high carbon case will show up as a dark layer at the surface of the part and may be measured with an accuracy dependent only on the power of the microscope available. If measured in the proper metallurgical microscope at 100 magnifications or more, there should be a standard and clearly understood method of measurement so that alleged depths can be made truly comparable, *i.e.*, it should be decided beforehand whether the case depth is to be regarded as the uttermost limit to which the carbon has penetrated or as the depth to which the carbon has penetrated effectively from the hardness point of view (if the latter, then the depth to which the carbon is 0·65 per cent. or over is a good standard of measurement).

The case depth is obviously a measure of the hardness depth. The hardness varies through the case, and so, of course, does the carbon content, both being quite low where the case ends and the core begins. The carbon content of the case is a very important matter and the following points should be noted :—

(*a*) The carbon content of the case at the surface should not exceed 1·0 per cent., otherwise quenching and grinding cracks are probable, cementite is present, and the case is unduly brittle as emphasised early in the paper.

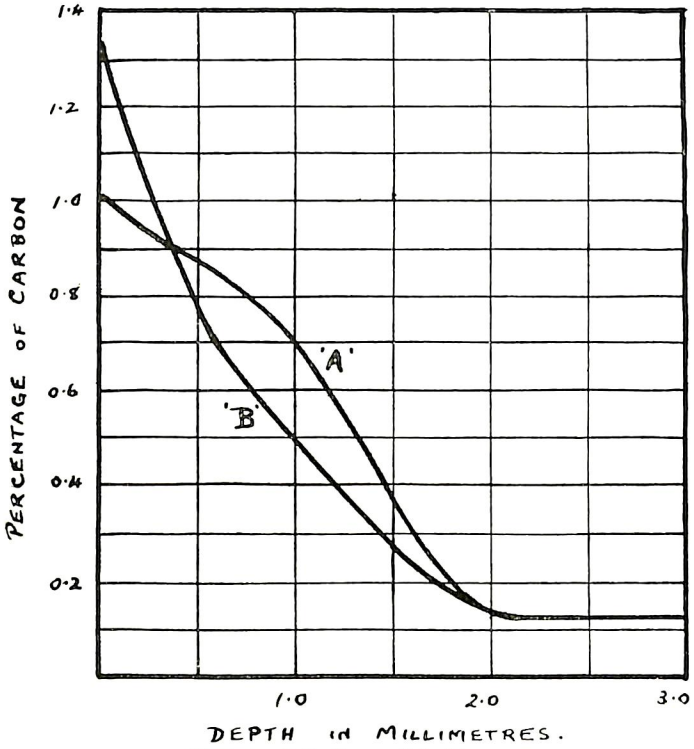
(*b*) The transition from case to core should not be too abrupt. A sharp line of demarcation between case and core denotes a potential cleavage plane and the breaking away of the case under ordinary working conditions is almost always the result of this fault, the dangers of which are not fully realised. This condition is usually associated with the high carbon surface mentioned in (*a*) and can be avoided by observing the conditions described in previous pages.

(*c*) The carbon content should not fall too rapidly below the surface. Fig. 1 compares the carbon gradient of the cases produced by two different compounds on the same steel under identical conditions of carburising for equal times.

FIGURE 1.

Carbon Gradient Through the Case.

Comparison of Two Compounds 'A' and 'B.'



Steel to B.S. Spec. 2 S. 14.
Carburised 12 Hours at 900°C.

In Fig. 1, compound 'A' is that so designated earlier in the paper and 'B' is an unsatisfactory proprietary brand of deplorable popularity. The carbon was estimated by turning off successive layers and analysing them. Note the superior results obtained from 'A' compound from the points of view of carbon content at the surface and effective depth taking the effective case as that which contains not less than 0·65 per cent. carbon.

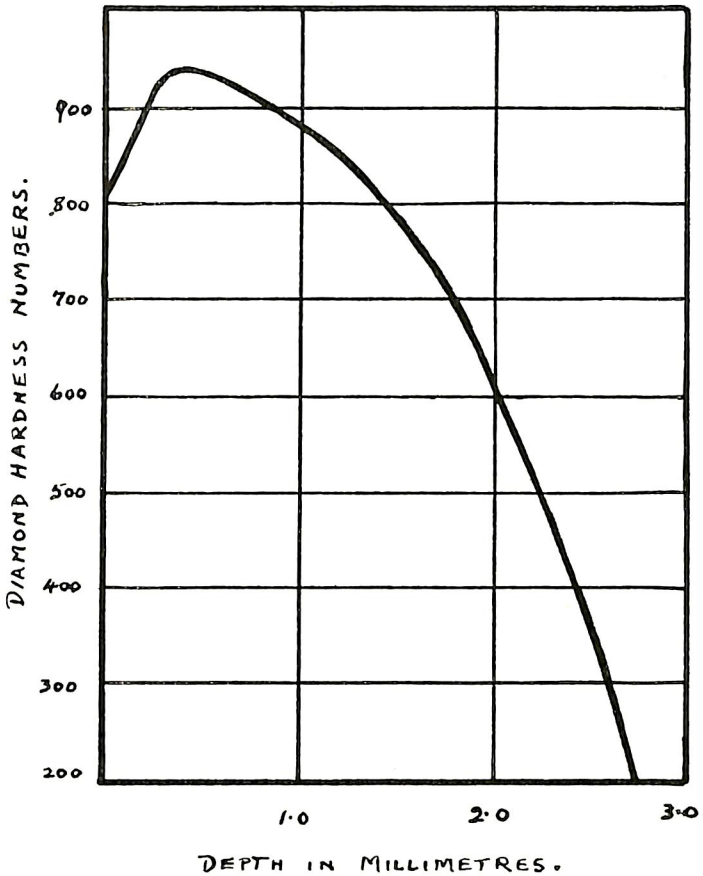
The total depth of effective hardness depends on the carbon gradient, but the hardness gradient appears to differ from the carbon gradient in that if layers are successively and carefully

ground off a case-hardened part, the hardness almost invariably increases slightly at first before falling away in the expected fashion. Possibly this phenomenon would not appear at all strange if we had extremely accurate methods of measuring the carbon contents of the layers, but we can only bear that in mind and note the determined facts. The author has once or twice actually found the carbon to reach a maximum ·005 - ·010″ below the surface, though not in the samples illustrated in Fig. 1. Fig. 2 shows the hardness gradient of a test bar recently treated and examined by the author.

FIGURE 2.

Hardness Gradient Through the Case.

TYPICAL SPECIMEN.



Steel to B.S. Spec. 2 S. 14.
Carburise 18 Hours at 910°C.
Total Depth of Carbon Penetration was 3·10 mm.

The fact that the hardness can be expected to rise slightly if anything, is well worth bearing in mind when a few thousandths only are removed in grinding operations. Nothing but the most careful grinding will give this result even when the amount removed is small, but if the amount removed *is* small and the hardness falls away, you must check your grinding conditions. They are not good.

If much of the case is removed by grinding the fall in hardness can be very serious. The remedy is obvious.

We can now give some consideration to the inspection of the core properties of the case-hardened part where these properties are important.

A Brinell hardness test on the core will determine its approximate tensile strength. An actual tensile test piece can be machined and broken when the Brinell is on the high or the low limit.

A nicked fracture test will in most instances be sufficient to decide the important question of the toughness of the core. An Izod test piece can be machined and broken when the appearance of the fracture leaves some doubt in the mind of the inspector.

The nicked fracture test should be carried out by sawing rather less than halfway through the section (an $\frac{1}{8}$" thick bonded emery wheel is ideal for the purpose) and breaking over the remainder with a few blows from a hammer. The number of blows should be kept down and 2 to 4 should be regarded as normal while one is the ideal. Breaking the part slowly (comparatively) in a press or similar machine is to be deplored as the apparent ductility is exaggerated thereby. The core fracture should be free from piping, and should be grey and tough but not necessarily fibrous. In fact, pronounced fibre can be regarded as an indication that the steel is of poor quality and many an advertisement showing the very fibrous fractures of case-hardened test bars does little credit to the steel-maker responsible and shows he has a very low opinion of the metallurgical knowledge of those who may chance to glance at the picture.

Very obvious fibre of this kind is invariably due to the existence of elongated slag streaks or other discontinuities in the steel. Wrought iron, for example, owes its fibrous fracture to anything up to 3 per cent. of slag, which simply increases the toughness across the "grain" of the material at the expense of its resistance to stresses parallel to the grain (*i.e.* parallel to the direction of rolling which produces the grain). Although Izod and similar tests of toughness are usually taken in such fashion that the stress applied is at right angles to the grain or fibre, the properties when tested transversely are obviously of importance in machined parts because at all sorts of fillets, collars, roots of teeth, undersides of boltheads, etc., the fibre runs out to the surface and these transverse properties come into play.

In addition, the slag streaks in the fibrous steel cause discontinuities in the case which are lines of weakness and therefore dan-

gerous. Maximum hardness cannot be obtained on the surface of such streaky material—particularly on surfaces at an angle to the grain.

That is all the author has to say in the meantime on case-hardening processes in general and pack-hardening in particular. Other hardening methods have considerable scope and popularity, but another pamphlet is required to do them justice.

TABLE No. 3.—DIAMOND HARDNESS NUMBERS.

Firth Hardometer Table for use with 136° Diamond Indenter and 120 Kg. or 30 Kg. Load.

Scale Division.	Diamond Hardness Number.	Scale Division.	Diamond Hardness Number.	Scale Division.	Diamond Hardness Number.	Scale Division.	Diamond Hardness Number.	Scale Division.	Diamond Hardness Number.	Scale Division.	Diamond Hardness Number.
2·20	1149	3·00	618	3·80	385	4·60	263	5·40	191	6·20	145
2·25	1099	3·05	598	3·85	375	4·65	257	5·45	187	6·25	142
2·30	1052	3·10	579	3·90	366	4·70	252	5·50	184	6·30	140
2·35	1007	3·15	561	3·95	357	4·75	247	5·55	181	6·35	138
2·40	966	3·20	543	4·00	348	4·80	242	5·60	177	6·40	136
2·45	927	3·25	527	4·05	339	4·85	237	5·65	174	6·45	134
2·50	890	3·30	511	4·10	331	4·90	232	5·70	171	6·50	132
2·55	856	3·35	496	4·15	323	4·95	227	5·75	168		
2·60	823	3·40	481	4·20	315	5·00	223	5·80	165		
2·65	792	3·45	467	4·25	308	5·05	218	5·85	163		
2·70	763	3·50	454	4·30	301	5·10	214	5·90	160		
2·75	736	3·55	441	4·35	294	5·15	210	5·95	157		
2·80	710	3·60	429	4·40	287	5·20	206	6·00	155		
2·85	685	3·65	418	4·45	281	5·25	202	6·05	152		
2·90	661	3·70	406	4·50	275	5·30	198	6·10	150		
2·95	639	3·75	396	4·55	269	5·35	194	6·15	147		

The Scale Divisions are Tenths of a Millimetre.

The Table for the Vickers' Machine is similar.

The B.S.I. Specification is No. 427. It gives full details and Tables covering the whole range.

TABLE No. 4.—BABY BRINELL TESTS.

Firth Hardometer Table for use with 2 m.m. Ball and 120 Kg. Load or 1 m.m. Ball and 30 Kg.

Scale Division.	Brinell Hardness Number.	Scale Division.	Brinell Hardness Number.	Scale Division.	Brinell Hardness Number.	Scale Division.	Brinell Hardness Number.	Scale Division.	Brinell Hardness Number.
3·00	418	3·80	255	4·60	170	5·40	121	6·20	89
3·05	402	3·85	248	4·65	166	5·45	118	6·25	87
3·10	387	3·90	241	4·70	163	5·50	116	6·30	86
3·15	375	3·95	235	4·75	159	5·55	114	6·35	84
3·20	364	4·00	228	4·80	156	5·60	112	6·40	82
3·25	351	4.05	223	4·85	153	5·65	109	6·45	81
3·30	340	4·10	217	4·90	149	5·70	107	6·50	80
3·35	332	4·15	212	4·95	146	5·75	105	6·55	79
3·40	321	4·20	207	5·00	143	5·80	103	6·60	77
3·45	311	4·25	202	5·05	140	5·85	101	6·65	76
3·50	302	4·30	196	5·10	137	5·90	99	6·70	74
3·55	293	4·35	192	5·15	134	5·95	97	6·75	73
3·60	286	4·40	187	5·20	131	6·00	95	6·80	71·5
3·65	277	4·45	183	5·25	128	6·05	94	6·85	70
3·70	269	4·50	179	5·30	126	6·10	92	6·90	69
3·75	262	4·55	174	5·35	124	6·15	90	6·95	68

The Appropriate B.S.I. Specification is No. 240.

TABLE No. 5.

BRINELL TABLE OF EQUIVALENT TENSILE STRENGTH.

Load of 3000 k.g. on Ball 10 m.m. Diameter.

Tensile Strength = Brinell Numeral × Factor.

Impres. Diam. in M.M.	Brinell Figure	Equivalent Tons per Sq. In. with Factor.			Impres. Diam. in M.M.	Brinell Figure	Equivalent Tons per Sq. In. with Factor.		
		·21	·23	·25			·21	·23	·25
2·40	653	137	150	163	4·75	159	33	36·5	40
2·45	627	132	144	157	4·80	156	32·5	36	39
2·50	601	126	138	151	4·85	152	32	35	38
2·55	578	121	133	145	4·90	149	31	34	37·5
2·60	555	116	128	139	4·95	146	30·5	33·5	36·5
2·65	534	112	123	134	5·00	143	30	33	36
2·70	514	108	118	129	5·05	140	29	32	35
2·75	495	104	114	124	5·10	137	28·5	31·5	34·5
2·80	477	100	110	119	5·15	134	28	31	33·5
2·85	461	97	106	115	5·20	131	27·5	30	33
2·90	444	93	102	111	5·25	128	26·5	29·5	32
2·95	429	90	99	107	5·30	126	26	29	31·5
3·00	415	87	95	104	5·35	123	25·5	28·5	31
3·05	401	84	92	100	5·40	121	25	28	30·5
3·10	388	81	89	97	5·45	118	24·5	27	29·5
3·15	375	79	86	94	5·50	116	24	26·5	29
3·20	363	76	83	91	5·55	114	24	26	28·5
3·25	352	74	81	88	5·60	111	23	25·5	28
3·30	341	71	78	85	5·65	109	23	25	27·5
3·35	331	69	76	83	5·70	107	22·5	24·5	27
3·40	321	67	74	80	5·75	105	22	24	26·5
3·45	311	65	72	78	5·80	103	21·5	23·5	26
3·50	302	63	69	76	5·85	101	21	23	25·5
3·55	293	61	67	73	5·90	99	20·5	23	25
3·60	285	60	66	71	5·95	97	20	22·5	24·5
3·65	277	58	64	69	6·00	95·5	20	22	24
3·70	269	56	62	67	6·05	94	19·5	21·5	23·5
3·75	262	55	60	66	6·10	92	19	21	23
3·80	255	53	59	64	6·15	90	19	20·5	22·5
3·85	248	52	57	62	6·20	89	18·5	20·5	22·5
3·90	241	50	55	60	6·25	87	18	20	22
3·95	235	49	54	59	6·30	85·5	18	19·5	21·5
4·00	229	48	53	57	6·35	84	17·5	19·5	21
4·05	223	47	51	56	6·40	82·5	17	19	21
4·10	217	45	50	54	6·45	81	17	18·5	20·5
4·15	212	44	49	53	6·50	80	16·5	18·5	20
4·20	207	43	48	52	6·55	78	16·5	18	19·5
4·25	201	42	46	50	6·60	77	16	17·5	19·5
4·30	197	41	45	49	6·65	75	15·5	17·5	19
4·35	192	40	44	48	6·70	74	15·5	17	18·5
4·40	187	39	43	47	6·75	73	15	17	18·5
4·45	183	38	42	46	6·80	72	15	16·5	18
4·50	179	37	41	45	6·85	70	14·5	16	17·5
4·55	174	36	40	44	6·90	69	14·5	16	17·5
4·60	170	35	39	43	6·95	68	14	15·5	17
4·65	167	35	38	42	7·00	67	14	15·5	17
4·70	163	34	37	41					

A. For most Steels, whether Carbon or Alloy, heat-treated in relatively small masses, the probable tensile strength will fall within the figure given by factors ·21 and ·23.

B. With Carbon Steels and certain Alloy Steels, annealed to give a low yield ratio, the probable tensile strength will fall within the figures given by factors ·23 and ·25.

C. When the physical condition of the Steel is not known and cannot be deduced, use range between factors ·21 and ·23 for numbers over 175 and between factors ·23 and ·25 for numbers below 175.

D The figures over 350 Brinell are of doubtful value.

TABLE 6.

Conversion Table for Hardness Figures.

Vickers or Firth Diamond Hardness.	Brinell.		Rockwell.		Sclero-scope.	Möh's Scale of Hardness
	Standard Ball.	Tungsten Carbide Ball.	C. 150 Kg.	B. $\frac{1}{16}$" Ball.		
1149	745	840	70	—	102	8·5
1052	712	812	68	—	98	—
966	682	794	66	—	94	—
890	653	760	64	—	91	—
823	627	724	62	—	87	8·0
763	601	682	60	—	84	—
710	578	646	58	—	81	—
661	555	614	56	—	78	7·5
598	514	555	52	—	73	—
561	495	525	50	—	71	—
527	477	514	49	—	68	—
467	444	444	46	—	64	7·0
418	401	401	42	—	59	—
396	388	388	41	—	57	6·5
357	352	—	38	—	53	—
323	321	—	33	—	49	—
281	281	—	29	—	44	6·0
237	235	—	21	101	—	—
202	201	—	13	94	—	—
171	170	—	4	88	—	5·0
140	140	—	—	79	—	4·5
121	121	—	—	72	—	—
110	110	—	—	66	—	—

TABLE 1.

THE CASE-HARDENING STEELS OF MOST INTEREST.

Specification Number.	COMPOSITION.														HEAT-TREATMENT °C.				PHYSICAL PROPERTIES.								Remarks.
	Carbon.		Nickel.		Chromium.		Molybdenum.		Silicon.		Manganese.		Sulphur.	Phos-phorus.	Car-burise.	Refine Core.	Harden	Temper	Tensile Strength. tons p. sq. in.		Elon-gation. %	Reduc. of Area. %	Brinell (of Core)		Izod ft. lbs.	Surface Hardness Pyramidal Diamond.	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Max.	Max.	Max.			Max.	Min.	Max.	Min.	Min.	Min.	Max.	Min.	Min.	
B.S.I. 2 S.14	·10	·18	—	—	—	—	—	—	—	·30	—	·90	·05	·05	930	900 W.Q.	780 W.Q.	200	32	—	20	50	140	200	40	850	Ordinary Case-hardening Mild Steel.
3 S.15	·10	·15	2·75	3·50	—	·30	—	—	—	·30	·20	·60	·05	·05	920	860 O.Q. or W.Q.	770 W.Q.	200	45	60	18	45	207	277	40	750	3% Nickel.
S.67	·08	·14	4·60	5·20	—	·10	—	—	—	·30	—	·35	·05	·05	910	830 O.Q. or W.Q.	740 O.Q.	200	40	60	20	45	183	277	50	700	5% Nickel.
S.83	—	·16	4·75	5·50	—	·30	—	·50	—	·30	—	·40	·05	·05	900	830 O.Q. or W.Q.	760 W.Q.	200	70	—	13	40	321	364	25	720	High Tensile 5% Nickel.
S.82	—	·18	4·00	4·50	1·0	1·6	—	·50	—	·30	—	·50	·05	·05	900	830 A.Q. or O.Q.	760 O.Q.	180	85	—	12	35	387	—	25	730	Nickel Chrom. C.H. Steel.
A Popular Gear Steel	·09	·13	3·00	3·75	·80	1·10	—	—	—	·25	·25	·40	·05	·05	900	830 O.Q.	770 O.Q.	180	55	70	14	40	255	321	22	730	Similar Lower Alloy Content.
Do.	,,	,,	,,	,,	,,	,,	—	—	—	,,	,,	,,	,,	,,	,,	,,	770 W.Q.	180	70	90	12	35	321	418	18	750	Ditto Water Hardened.
A 5 per cent. Nickel Steel	·10	·15	4·6	5·4	—	·30	—	—	—	·30	·30	·50	·05	·05	900	830 A.Q. or O.Q.	760 W.Q.	200	70	87	13	40	321	387	25	720	Similar to S.83.
Do.	·13	·15	5·0	5·4	·14	·30	—	—	—	,,	,,	,,	,,	,,	,,	—	820 O.Q.	200	65	—	16	45	293	—	30	700	Ditto. Single Quench Treatment.

O.Q. = Oil Quench. W.Q. = Water Quench. A.Q. = Cool in Air.

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